AN EFFICIENT METHOD FOR RURAL ELECTRIFICATION GRID DESIGN

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Abstract

This paper investigates the optimization of the electricity grid network in rural community of Chegutu district, in Zimbabwe. The Kruskal's algorithm is used for the minimum spanning tree to carry out the optimization process.The project seeks to find how a network with a number of possible connections can have the least possible distance. The main objective of the optimization procedure is to minimize the total distance of the network connections, so as to minimize resources that are used when carrying out projects. Rural Electrification Agency has been failing to meet their targets for extension of the electricity grid network because of shortage of resources and input capital, thus the researcher adopts the idea of network optimization as a way of saving resources so that they can be used for other projects. The researcher used the algorithm to carry out the manual computation of the optimization process and also used C sharp programming language to create a code that is able to minimize the total distance of the network. In this dissertation the Kruskal's algorithm has been translated into a simple model that can be easily used to map distances between nodes and vertices. The model presented in this dissertation help network service providers such as electricity, telephone and information technology to optimize their network resources so as to save money and resources for other uses in the future. The optimisation process shows that a total of 74km of 11kV power line could be saved from the network.

Keywords: Minimum spanning tree, Electricity transmission line, Rural Electrification, optimisation

Introduction

Rural Electrification Agency (REA) is a statutory body responsible for providing electricity to the rural communities in Zimbabwe. It was initiated in 2002 following the enactment of the Rural Electrification Fund Act (2002) . The major thrust of the Rural Electrification Fund was to ensure that electricity reaches all communities including the less privileged communities.

Overview of REA and OR techniques

Rural electrification agency provides electricity to rural schools, clinics, business centres and other service centers in the rural areas. The need to have electricity in rural areas has been accelerated by the land reform programme, which has lead to the migration of people from urban communities to newly allocated farms in rural areas. This has resulted in the growth of school, business and health centres thus the increased need for electricity in these communities. Electricity is also needed for the irrigation schemes initiated by the government as part of the land reform programme. REA has been established with the mandate to facilitate the development of grid network and off grid electricity infrastructure in rural areas of Zimbabwe . (Expanded Rural Electrification Brochure, Harare, 2007)

Projects carried out by REA are lagging behind because of financial constraints. These projects are funded from various contributions, and these include a 6% levy on all Zimbabwe Electrical Supply Authority (ZESA) electricity sales, customer contributions, borrowings, income generating activities, donations and grants from governments, organizations and individuals, however these funds are inadequate to carter for all the resources needed to execute the projects as per schedule, thus Operations Research (OR) techniques can assist in optimizing the few available resources to make the best use out of them.

A case study of Chegutu district in Mashonaland West province is used in this project to determine how OR techniques can be applied to optimize routes used to install electricity lines. Operations research is used in representation of world class systems to find ways of solving complex problems using algorithms; it also involves mathematical procedures and modeling. Various OR techniques can be used such as dynamic programming, longest or shortest route networks, minimum tree spanning network and minimum or maximum flow networks. The success of the project would result in the optimum use of available resources thus the few available resources can be used for more grid extension lines.

Background of the problem

REA is using an approximation of the shortest distance method to establish the least distance from the existing grid network to the proposed site; this is an ineffective method for optimization of few available resources. This method does not produce an optimum network with least cost as it depends on the starting node of the network, the least distance of a certain route in a network can be distorted if the starting node is changed.

Approximation of the shortest distances from substations to proposed sites tend to produces longer routes than required which are not optimum, thereby consuming more resources for the project. Many schools in rural areas are failing to pay the required amounts of money for them to have an electricity connection, thus this is hindering the development of new educational curriculum where the use of computers is highly recommended. Students from rural schools normally have poor pass rates because their study time is limited by daylight, very few of the can afford lamps and alternatives sources light energy to use when studying. Schools require electricity to enable them to use computers, printers, fax machine and other electrical gadgets. Clinics require electricity mainly for the sterilization of clinic equipment and other clinical activities. The newly resettled farmer have increased the need for electricity in rural communities as they are establishing small business at growth points such as grinding mills, bottle stores and butcheries.

This increased need for electricity in rural communities coupled with in effective methods of establishing routes for electricity connections has put a strain on the few available resources resulting in many communities not having electricity. Financial constraints are hindering the purchase of required material, electric cables, labour payments and this has resulted in the shortage of resources for installation of electricity grid extensions. The Kruskal’s algorithm for minimum spanning tree can be applied to optimize the electricity network so that the few available resources will enable more grid extensions. The minimum spanning tree method is used to determine the least distance from the nearest supply node to the destination node. It makes use of an algorithm that repeats iteration at some point and this helps in establishing the least distance from source to supply.

When REA was established it aimed at providing electricity to 80% of rural communities by 2012, but as for today none of the 10 provinces has reached a 50% mark in terms of electrification. *(Expanded Rural Electrification Brochure, Harare, 2011)*Funding is the major drawback for the projects, since funds are not easily accessible. REA is funded through the Rural Electrification Levy, Fiscal allocation from the national budget, Grants and donations from any government, organization or individuals Contributions from customers who require electricity. However these funds are inadequate for the completion of all the projects, thus an alternative solution such as optimizing routes for electricity connections can be used to utilize the few available resources for more grid extensions. The minimum spanning tree method, an Operations research technique can be used to optimize these routes for electricity connections.

When establishing the electricity line network REA tries to avoid network routes that may be potential electrical hazards. They avoid routes with major river crossings, railway crossing, telephone lines and elevated terrains; these are mainly considered when they want to establish routes because they may cause electromagnetic interference when they are within a certain radius from the electricity lines

Table: 1 Number of electrified schools, health centres and business centres in Chegutu district.

	Total schools	Electrified schools
Primary schools	75	40
Secondary schools	28	9
Health centres	19	7
Bussiness centres	9	5
Total		51%

Information in the Table 1 shows that many projects in this district have reached almost a 50% mark in terms of electrification of schools, hospitals and business centres. This can be improved by using the minimum tree spanning method which is a cost effective method for establishing routes for electricity connections.

Literature review

2.1 Electricity transmission line requirements for REA

Electricity transmission line for REA are used to supply electricity from the existing substation to various proposed sites which might be a school, clinic or a business centre. The transmission line may be composed of either a High Voltage (HV) or a Low Voltage (LV) line. The type of line to be used for a certain project is determined by two main factors which are the power requirements of the proposed site and the zone in which the proposed sites are situated. Projects are grouped into zones depending on the distance between the nearest supply and the proposed site as shown Table 2.

Table 2: Zones in which various projects lie (Rural Electrification Brochure, Mash west province, 2011 unpublished)

Radius distance from source to site	Zone in which the project lies
5km	1
10km	2
15km	3
20km	4
25km	5

There are three main transmission line voltages offered by REA and these are

- Low voltage transmission - for household consumption and domestic use.
- 11kV transmission- required for a distribution network with a radius up to 15km and this is for light commercial use for example, supermarkets, butcheries, schools and grinding mills.
- 33kV transmission - for a radius up to 25km required heavy industrial use.

Rural electrification challenges globally

Roughly 22% of the world's population still does not have access to electricity (IEA, 2009). In 2008, this represented 1.5 billion people, most of whom lived in remote areas often difficult to access and therefore to connect to national or regional grids. The International Energy Agency estimates that roughly 85% of the people without electricity live in rural areas of developing countries, mostly in peri-urban or remote rural areas *(IEA, 2009).*

Methods used for optimizing routes

Geographic Information Systems GIS with Dynamic Programming (DP)

GIS platform is used for the selection of the minimum cost route as well as its economic corridor for electricity installation, where geographic data installation, maintenance, operation costs, land use, etc and computing results are represented in raster format instead of vector format. GIS raster structures are basically a regular matrix of square cells where each cell represents an elementary area and position. The detail of the geospatial analysis depends on the size of the elementary cell resolution. The raster format allows adopting dynamic programming (DP) for all of the studied geographic areas. An original application of advanced DP optimization to raster data is carried out in an iterative way for the selection of the optimal route path. In GIS raster routing, all costs must be associated with terrain surface. When low resolution for example, cell area of 1×1 km, that is, 1 km of resolution is used, the costs of the sections of overhead lines, including conductors, insulators, and support structures are associated with a cell area of the map grid without specifying the location of the support structures towers. This concept simplifies the routing process by assuming that the cost of the overhead transmission line components is uniformly distributed along the path a cost per kilometer (Monteiro et al 2005).

Operations Research Application

Operations research techniques are used in optimizing network electricity grid. The researcher analyzes some methods which are best applicable in the optimization process. The minimum spanning tree method is one the best methods that can be used in optimization of an electricity network grid. A Minimum Spanning Tree (MST) or minimum weight spanning tree is a spanning tree with weight less than or equal to the weight of every other spanning tree (Fredman and Willard, 1995).

(1) Minimum Spanning Tree algorithms.

The researcher analysed the first algorithm for minimum spanning tree developed by Czech scientist Borůvka in 1926; its purpose was an efficient electrical coverage of Moravia (Nešetřil, 2001). There are now main two algorithms for MST commonly used, Prim's and Kruskal's algorithm both are greedy algorithms that run in polynomial time. Reverse-delete algorithm is another greedy algorithm not as commonly used, which is the reverse of Kruskal's algorithm. On all the algorithms analysed, the researcher considered the Kruskals algorithm as it is the best method for optimising a network as it mainly consider edge weights which represent the actual distance between centres.

Case study audit

Rural community of Chegutu district has been used as a case study to provide a detailed outline of the optimisation process. The operation of Kruskal’s algorithm for the minimum spanning tree is used to optimize the distances between network connections. The study uses existing energy grid network of Chegutu district as the sample area for study. Chegutu district has a total area of 5307km^2 and a population of 224 589 people according to 2002 census. The total population used in this research consists of 75 primary schools, 28 secondary schools and 19 clinics. Data used for this research was obtained from existing data bases of Rural Electrification Agency of Mashonaland West Province. Important data of electrified communities and non electrified communities was considered from the database in form of statistical work sheets. These work sheets included data of distances from source to point of supply and the required line voltages for the connections which have been used for construction of the existing energy grid network.

Analysis of schools and clinics that are not electrified

Primary schools, secondary schools and clinics in this district have been analysed on a geographical map to establish their actual location on the grid network. Schools and clinics that have not been electrified are represented as blue circles in the map, and those that have been electrified represented as deep red circles in Fig 1. The electricity grid network have not yet been extended to the areas highlighted by the blue colour in the map even though some of these areas lie in the regions which have an already existing energy grid, 42% of schools and 58% of clinics in Chegutu district are not yet electrified. Data of schools and clinics that have been electrified has been computed from REA statistical charts and compared with the total number of schools and clinics in the district to establish those which are not electrified. Some of these highlighted areas in the map have already been surveyed by REA to establish where the nearest point of supply can be. However the electricity grid could not be extended to these locations because of financial constraints which are hindering the purchase of the required material and hiring of required manpower.The number of electrified and nor electrified schools and clinics are summarized in Table 3.

Table 3: Number of electrified and non electrified schools and clinics

	Electrified	Not Electrified
Primary School	40	35
Secondary School	19	9
Clinics	12	7

The electricity grid network has to be extended to all the areas highlighted in the mapin Figure 1; however some of these areas are not yet part of the electricity grid because of high installation cost/km. An analysis of the factors contributing to the total cost of establishing an 11kv transmission line per kilometer was done. The total cost include the cost of poles used for supporting the lines, these can be made of either treated wood or concrete. Poles are one of the most of the expensive materials in establishing an electricity grid with a cost averaging almost 35% of the total cost of materials. The cost per pole generally varies from $100 to $250. Some of the things that contribute to the total cost include insulators, copper conductors and the labour. The researchers compiled the cost data from job cards of projects that have already been done by REA and quotations of projects to be carried out and came up with a summarized form of cost involved. The breakdown of cost of components' used by REA for an 11kV transmission line is shown in Table 4.

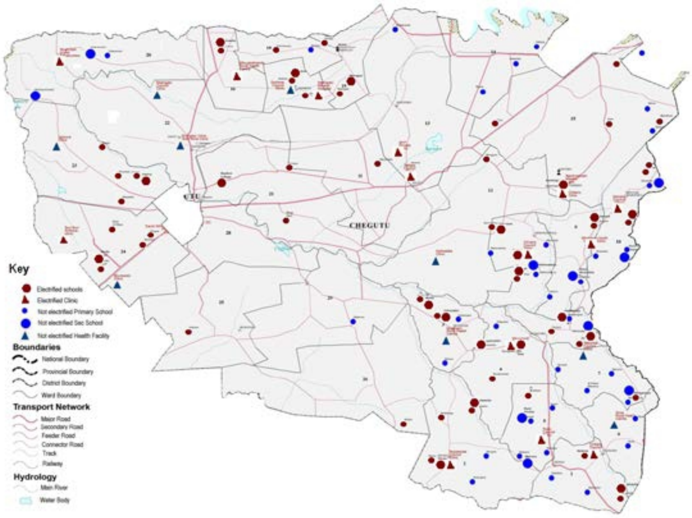

Figure 1: Map showing electrified and non electrified schools and clinics.

Table 4: Breakdown of cost for an 11kV line

Component	Description	Cost/km
1. Poles	10.6m-12m long	$3500.00
2. Conductors	1/0 (53mm^2) ACSR	$2900.00
3. Pole top assembly	Pin insulators ,cross arms ,etc	$1950.00
4. Guys	Cable, attachments	$850.00
5. Labour + Transportation		$2800.00
Total		$12000.00

Analysis of the existing grid line

Data collected vital for the construction of the energy grid included

- Point of supply that is, the destination for the electricity line
- Proposed feeder or source where the electricity line was coming from
- Required voltage for the line, as for this project the researcher concentrated on 11kV lines only
- Length of line from proposed feeder or source to point of supply.
- Status of the line, weather it is electrified or not

The general framework of the existing energy grid from ZESA, was used to come up with the grid network for electrified schools and clinics. The location of main substations on the map was established and some of the connections for the existing energy grid for Chegutu District. The backbone of energy grid network for Chegutu district consist of two high voltage lines which pass through Chegutu from Norton going to Kadoma. They basically form the trunk of the spanning tree and all other branches are derived from the trunk of this tree. Nodes represent names of different centres such as schools and clinics. These nodes have been established using coordinates from the map and the GIS software. Each node highlighted has its own x and y coordinates. The existing grid network is shown in the map in Fig 2. The high voltage line cannot be optimized since it lies within the national grid. The existing electricity grid connects substations and electrified centres such as schools and clinics, and it covers a total distance of 379km. This network consists of high voltage and low voltage lines and the centres served by these lines add to a total of 59 schools and 12 clinics. The 11kV line supplies electricity to schools, clinics, business centres and other connections. The greater part of Chegutu district has 11kV connections because it is a rural community and they do not have heavy industry which requires high voltages. The map in Fig 2 shows the proposed line connections in areas that do not have electricity.

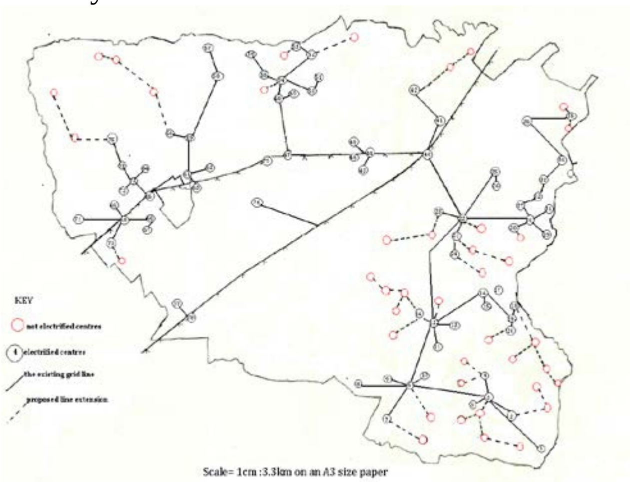

Figure 2: Existing energy grid network for Chegutu district.

The existing electricity grid shown on the map in Fig 3.2 covers a total distance of 379km. This network has been modeled using Kruskals algorithm so as to optimise the total distance.

Methodology

Kruskal’s algorithm has been applied in creating a model of an optimised grid network for Chegutu district. This model forms a spanning tree which is a sub graph that is a tree and spans out to reach all the vertices of the original graph. Vertices to be reached by the tree include schools, clinics and substations. Computation of the graph was done using Visual Studio C-Sharp programming to create a minimum spanning tree program that is capable of establishing an optimized network grid.

3.1 Kruskal’s algorithm

Kruskal's algorithm processes the edges of a network in order of their weight values from smallest to largest, for the MST contruction each edge that does not form a cycle with edges previously added is considered for the network span. Kruskal's algorithm makes heavy use of set operations "find" and "union". Optimally implemented, the "find" and "union" operations on sets grow very slowly with the number of elements in the disjoint sets (Kruskal 1956)).

3.2 Algorithm

Let *(v)* = vertices or nodes in the network
(u) =edges in the network
(s) = set for spanning tree containing edges *(u)* and nodes *(v)*

- Start with an empty set S, and select at every stage the shortest edge that has not been chosen or rejected, regardless of where this edge is situated in the graph.
- Select edge *(u)* with the least weight *(w)* and connect it to node *(v)*
- Repeat stage 2 until all edges are connected to the network
- Set S will ultimately contains the edges of the MST for each (*u*, *v*) taken from the sorted list
    - o do if FIND-SET *(u)* = FIND-SET *(v)*
    - o then S $\leftarrow S \cup \{(u, v)\}$
    - o UNION *(u, v)*

Model for Kruskal's algorithm

The flow diagram of the Kruskal algorithm is summarized in Fig 3.

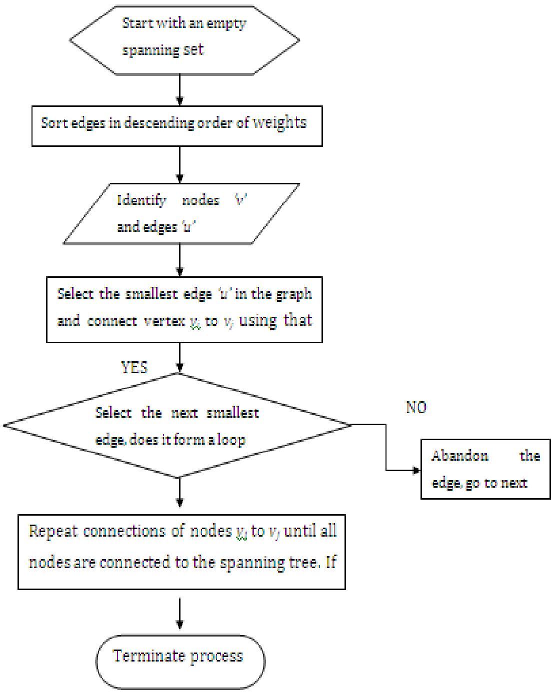

Fig 3: Model of Kruskal's algorithm

Construction of the minimum spanning tree.

The data used to create the minimum spanning tree whereby the distances between source and point of supply are considered from the least to the greatest. The distances between sources to supply represent the edge *(u)* and the electrified centres represent the nodes or vertices *(v)*. This distance denoted by *(u)* can be calculated using coordinates between two points, an Example to establish the distance between Mupfure College (37.29, 62.7) and Selous Main (37.62, 61.38). Therefore the distance between these two points can be calculated as

Distance =U is such that

$$\boldsymbol{U} = \sqrt{(\boldsymbol{x}_2 - \boldsymbol{x}_1)^2} + \sqrt{(\boldsymbol{y}_2 - \boldsymbol{y}_1)^2} \quad \ldots\ldots\ldots (1)$$

$$\boldsymbol{U} = \sqrt{(\mathbf{37.29 - 37.62})}^2 + \sqrt{(\mathbf{62.7 - 61.38})}^2$$
$$\boldsymbol{U} = \mathbf{1.32}\boldsymbol{km}$$

The optimised energy grid network is constructed by joining edges to vertices starting from the least distance to the greatest. Fig 4 shows the initial stages of the network construction for some of the centres with the least distances.

The total distances covered can be calculated as

$$T_{total} = min \left\{ \sum_{u=1}^{v-1} W_T\,(u) \right\} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where $W_T(u)$ represents the weight assigned to edge *(u)*
U_T defines the set of edges in the complete tree

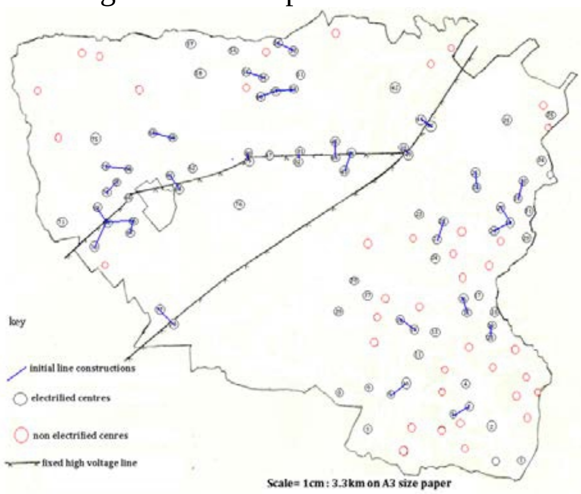

Fig 4: Initial construction of the grid using Kruskal’s algorithm

The connections of edges to vertices show how the minimum spanning tree can be computed manually step by step using the Kruskal’s algorithm. Kruskal's algorithm enables the formation of an optimized network through reduction of the total distance for the network by avoiding redundant connections.

The complete optimized grid network

The construction of the energy network grid was completed following the procedure of the Kruskal's algorithm using the data of the remaining schools and clinics. Construction of the network was completed considering distances from the least to the greatest according to the algorithm. The connecting edges are joined from the nearest point of supply which can provide the required voltage considering that there would no interference between the source and the point of supply. Substations are situated in areas which might require voltage to be stepped up or down depending on the required level. The coordinates were generated using Geo referencing method of GIS.

The network constructed shows the two main electricity lines in Chegutu district that is, 11kV and 33kV. The 33kV line is not part of the optimization process since it is a high voltage line. The network shows edges and vertices connected according to the Kruskal's algorithm. Each vertex or node has been assigned a number and this number represents the name of that centre. The edges connecting the nodes are shown in lines that is, the blue lines show 11kv lines connecting schools, clinics and substations whilst the black line is main line for high voltage connection. There are 9 main substations in chegutu district and these are used to either step up or step down step down the voltage depending on the required voltage. The substations, schools and clinics are all referred to as nodes in the network formation. The complete network manually computed using Kruskal's algorithm is shown in Fig 5.

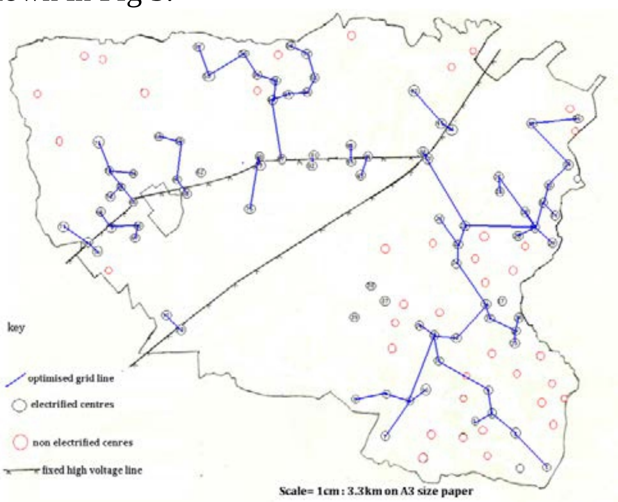

Fig 5: Electricity grid network computed manually

Computer program for Kruskal’s algorithm

A computer program for Kruskal’s algorithm was generated as a faster method of optimizing the grid network. The program code was created using Visual Studio C Sharp programming language. The researcher created codes for the form, buttons, and construction of nodes, edges and minimization of the total distance. The code created enables the user to interface with the form. The interface enables the user to put the input data for example, nodes of the network and distances between nodes of the spanning tree. The form has a solve button which acts as the process command, whereby the code enables the nodes to join using minimum distances following Kruskal’s algorithm. After processing the program displays data of a minimized network on an output form. By running the program the researcher was able to come up with an interface form that can be used to solve problems of minimum span or cost using Kruskal’s algorithm. The sample of the form created is shown in the Fig 6.

Results

Analysis of the total distance of the existing grid network was done using Kruskal’s algorithm which was compared with existing grid that was developed manually and using first-come- first serve (FCFS).

The total distance of an optimized network was calculated to be 314.26 km and shown in Fig 7. While the total distance of the existing network was calculated to be =378.76 km

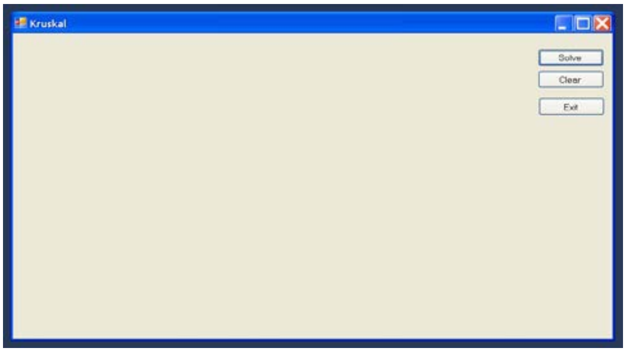

Fig 6: Form created from the program code

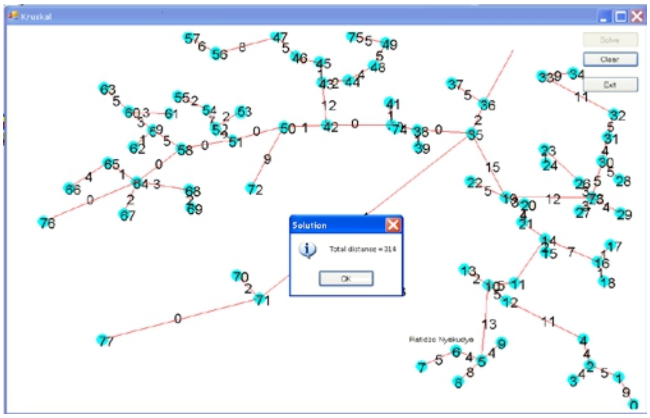

Fig 7: Optimized network from C sharp programming

The deviation of 74km is the total distance that can be saved from the existing grid using the algorithm. This distance can be used for grid extension to enable non electrified centres to receive electricity. The material that was to be used for the 74 km can be used to electrify many centres that require small distances.

The total cost of establishing an 11kV line is around $12000/km, thus the saving will be:

=$12 000×74km

=$888 000

The amount of $888 000 can be saved by optimizing the grid and this capital can be used to carry put other electrification projects that are lagging behind because of shortage of capital resources

Conclusion and Recommendations

The researcher used Kruskal's algorithm which proved the algorithm can optimize a network to produce the least possible total distance of a network. The main goals achieved in this project can be summarized as

- Reduction of resources used when constructing a network grid
- Establishment of routes with the least possible cost

The research has enabled construction a computer program for the optimization of the network. The electricity grid network with a minimum span has been created and has enabled the reduction of the total distance of the network by 74km which is worth $888 000. The 74km worth of resources can be used for grid extension to those areas which do not have electricity. These resources can go a long way in expanding the grid since many centres require extensions ranging from 1 to 5km. further work can be done to establish coordinates for schools that are not yet electrified so as to extend the electricity grid using Kruskal's algorithm for the minimum spanning tree.

Further research can improve the computer model for Kruskal's algorithm so that the program can include a form or an interface for entering the coordinates of schools rather than using distances between schools. Further research can also be done in integrating Geographic Information Systems and Kruskal's algorithm for it to be easier to map the grid in areas that do not have river crossings and elevated terrains.

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